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The relationship between dual-tasking and processing speed in healthy aging

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Abstract

Although studies report age-related declines on tests of executive function, not all executive tests show age differences, including the dual-task paradigm. As processing speed is known to decline with age, it is possible that changes in speed contribute to the variation in age-related decline found on different tests of executive function. In this study, the effects of age and processing speed on different executive tests in the same group of younger and older adults were investigated. Fifty-nine (n = 28 males & n = 31 females) younger adults (M_{age} = 21.49; *SD* = 2.54) and N = 52 (n = 22 males & n = 30 females) older adults (M_{age} = 72.04; *SD* = 4.99) were assessed on the following battery of measures: processing speed and the executive functions of dual-tasking, inhibition, set-shifting, and updating. Older adults performed significantly worse than younger adults on all executive function tests except dual-tasking. In addition, age, rather than processing speed, predicted executive function performance on executive tests of inhibition, set-shifting and updating tests. These findings confirm that dual-tasking does not decline with age and the age differences found on tests of inhibition, set-shifting and updating are not simply explained by processing speed.

Introduction

Frontal-executive functions refer to a series of complex cognitive skills important for individuals to successfully engage in purposeful, goal-directed behaviour, especially when faced with novel or difficult situations (Lezak, 1995). Executive functions include processes such as inhibition, flexibility, updating, initiation, planning, purposive action and self-monitoring. Impairments in executive functions are commonly associated with prefrontal damage (Luria, 1966; Stuss, 2011). As the prefrontal cortex is particularly vulnerable to age-related reductions in overall cortical volume, cortical thickness and white matter compared to other brain regions (Driscoll et al., 2009; Fjell et al., 2009), neuropsychological models of cognition across aging propose that the cognitive changes associated with healthy adult aging are due to a normal phenomenon of deterioration in the prefrontal cortex (MacPherson, Phillips, & Della Sala, 2002; Moscovitch, & Winocur, 1992; West, 1996; see MacPherson, & Cox, 2017).

A considerable number of cognitive aging studies have reported that age-related performance declines in executive functions using both standard neuropsychological tests and experimental paradigms (Mittenberg, Seidenburg, O'Leary & DiGiulio, 1989; Daigneault, Braun & Whitaker, 1992; MacPherson et al., 2002; Fisk & Sharp, 2004; Lamar & Resnick, 2004; de Frias, Dixon & Strauss, 2006; Johnson, Logie & Brockmole, 2010). However, there are some tests where age-related differences are less consistently found (for a review, see MacPherson & Della Sala, 2015). For example, older adults have been found to perform as well as or better than younger adults on the Cognitive Estimation Test (CET) (Axelrod & Millis, 1994; Della Sala, MacPherson, Phillips, Sacco & Spinnler, 2003; Gillespie, Evans, Gardener & Bowen, 2002; MacPherson et al., 2014; Scarpina, D'Aniello, Mauro, Castelnuovo & MacPherson, 2015). Another widely used fronto-executive test, letter fluency, does not always show age decline or may in fact improve with age (Henry & Phillips, 2006; Lamar & Resnick, 2004; Parkin, Walter & Hunkin, 1995). Therefore, age effects are not consistently reported on all executive tests.

Another executive test where the effects of age are varying is the ability to perform two tasks simultaneously (i.e., dual-tasking; see MacPherson, 2018), and this is thought be due to the nature of the dual-task paradigm adopted. When the two tasks compete for the same cognitive resources, there is a large dual-task decrement found in younger adults in their late teens, 20s and 30s, and this decrement increases further in older adults aged in their 60s to 90s (Hartley & Little, 1999; McDowd & Craik, 1988; Naveh-Benjamin, Craik, Guez & Kreuger, 2005). In other studies, where the demands of the two individual tasks are not calibrated to the ability of each participant, older adults in their 60s and 70s also show age-related dual-task differences (Anderson, Craik & Naveh-Benjamin, 1998; Craik, Govoni, Naveh-Benjamin & Anderson, 1996; Craik, & McDowd, 1987). However, as single task performance is not equated across age groups, any group difference in dual-tasking ability may have arisen from differences in baseline abilities in the two component tasks. Indeed, when the demands of the two tasks are calibrated to the ability of each individual to equate single task performance across groups, dual-task ability is unaffected in older adults aged 60-80 years (Baddeley, Bressi, Della Sala, Logie & Spinnler, 1986; Della Sala, Foley, Beschin, Allerhand & Logie, 2010; Logie, Cocchini, Della Sala & Baddeley, 2004; MacPherson, Della Sala & Logie, 2007), but is significantly impaired in similarly aged Alzheimer's disease patients (Baddeley et al., 1991; Della Sala et al., 2010; Foley et al., 2011, 2013; Kaschel et al., 2009; Logie et al., 2004; MacPherson et al., 2012).

Salthouse (1996) proposed the processing speed theory, which states that age-related differences on cognitive tests are due to declines in the rate that the fronto-executive system can perform simple operations (i.e., speed of processing). The influence of processing speed on the relationship between age and performance on fronto-executive tests has been found on tests of fluid intelligence (Salthouse, Fristoe, McGuthry & Hambrick, 1998), reading and computation span (Salthouse & Babcock, 1991), working memory (Salthouse, 1992), and recall, reasoning and spatial abilities (Salthouse, 1993). Processing speed also influences performance on executive tests. For example, in studies involving adults aged 18 to 90+ years, Salthouse reported that age effects on the Stroop and Tower tests (Salthouse, 2005), as well as a variant of the Trail Making test (Salthouse, 2011) were entirely explained by the relationship between age and speed. Fisk and Warr (1996) showed that processing speed also has an attenuating effect on age differences in random letter generation when comparing younger (20-33 years) and older (60-80 years) adults. Additionally, Fristoe, Salthouse and Woodward (1997) demonstrated a similar attenuating effect of processing speed on Wisconsin Card Sorting Task (WCST) performance when comparing younger (18-38 years) and older (60-86 years) adults.

However, while speed of processing clearly plays a role in the age-related differences associated with executive functions, such age differences are not always entirely removed by speed of processing (Keys & White, 2000; Verhaeghen, Cerella & Basak, 2006; Bugg, DeLosh, Davalos & Davis, 2007). For example, in adults aged 20-89 years, both Stroop test and WCST performance continue to show age differences when controlling for processing speed (Salthouse & Meinz, 1995; Bugg et al., 2007). A meta-analysis of task switching established an effect of age beyond general slowing, at least for overall task switching costs (Verhaeghen & Cerella, 2002). Therefore, processing speed cannot fully account for age-related effects on executive tests (cf., Salthouse et al., 1998).

No study appears to have examined the role of processing speed on dual-tasking performance. Studies to date have tended to explore the relationship between fronto-executive performance and speed of processing only on those cognitive tests that demonstrate age effects. The current study examined the effect of age on dual-tasking, as well as fronto-executive tests of inhibition, set-shifting and updating (see Miyake et al., 2000) in the same younger and older groups, and considered how any changes may relate to those of speed of processing.

Methods

Participants

One-hundred and eleven participants took part in this study: N= 59 healthy right-handed younger adults (n = 28 males & n = 31 females) and N = 52 healthy right-handed older adults (n = 22 males & n = 30 females). The healthy younger adults were all native English speakers recruited through the University of Edinburgh's Student and Graduate Employment website. They had a mean age of 21.49 years (*SD* = 2.54, range = 18-29; male: *M* = 21.75, *SD* = 2.56; female: *M* = 21.26, *SD* = 2.53) and a mean of 15.02 years of full-time education (*SD* = 1.72, range = 12-17; male: *M* = 15.29, *SD* = 1.61; female: *M* = 14.77, *SD* = 1.8). The healthy older adults were community dwelling, native English speakers recruited from the Department of Psychology volunteer panel at the University of Edinburgh. They had a mean age of 72.04 years (*SD* = 4.99, range = 65-84; male: *M* = 71.64, *SD* = 5.34; female: *M* = 72.33, *SD* = 4.78) and a mean of 14.87 years of full-time education (*SD* = 2.51, range = 10-19; male: *M* = 14.55, *SD* = 2.43; female: *M* = 15.1, *SD* = 2.59).

Participants had no known history of traumatic, neurological, psychiatric or physical disorder, and no history of alcohol/drug abuse. None of the participants met the criteria for global cognitive disorder using the 6-item Orientation-Memory-Concentration Test (6-CIT; Katzman et al., 1983), derived by regression analysis of the Blessed Information Memory

Concentration Scale (BIMC; Blessed, Tomlinson, & Roth, 1968) and validated in the UK for primary care usage (Brooke, & Bullock, 1999).

Measures

Inhibition. The *Colour-Word Interference Test (CWIT)* from the Delis–Kaplan Executive Function System (D-KEFS: Delis, Kaplan & Kramer, 2001) was administered to assess inhibition. Three of the four *CWIT* conditions were administered (i.e., *Colour Naming, Word Reading and Inhibition*). In the *Colour Naming* condition, participants were presented with a page of squares printed in blue, green and red. Participants were asked to name the colours out loud, as quickly and accurately as possible. In the *Word Reading* condition, participants were presented with a page of colour names (i.e., blue, green and red) in black ink. Participants were asked to read the words aloud, as quickly and accurately as possible. In the *Inhibition* condition, participants were presented with colour words (i.e., blue, green and red) printed in incongruent ink colours (e.g., 'blue' printed in red ink). Participants were asked to name the colour of the ink of each word, as quickly and accurately as possible. The time to complete was recorded for each condition.

Set-shifting. Set-shifting was assessed using *The Trail Making Test* (*TMT*) (Reitan, 1958). In part A *(TMT-A),* participants were asked to draw a line connecting 25 circled numbers in ascending numerical order, as quickly as possible, without lifting their pencil off the paper (e.g., 1, 2, 3…). In part B *(TMT-B),* participants were asked to draw a line connecting 25 circled numbers and letters, alternating between ascending numerical and alphabetical order (e.g., 1, A, 2, B, 3, C…), again as quickly as possible, without lifting their pencil off the paper. Performance taken as the time to complete *TMT-B* divided by the time to complete *TMT-A* (i.e., B/A is the *TMT proportion score).*

Updating. A modified version of the *Brown-Peterson Task (*Brown, 1958; Peterson & Peterson, 1959; Sebastian, Menor & Elosua, 2006) was administered to assess updating. A computerized version of the task was created with E-prime 2.0 to control the stimulus presentation duration. Participants were asked to read aloud two consonants (e.g., D, P) presented on the computer screen for 1.5 seconds. Immediately following this, a three-digit number was presented and participants were asked to subtract three from that number and then from each successive answer for an interval of 7, 14 or 21 seconds. At the end of the retention interval, a question mark appeared on the computer screen, and participants were asked to recall the two consonants previously presented. There were 7 trials for each time interval, which were randomly administered, resulting in 21 trials (i.e., 42 consonants). Four scores were obtained for this task: (a) the total number of correctly recalled consonants in their correct order; (b) the total number of errors generated, including switching of order, false recall, omissions, and perseverations; (c) the number of perseverations generated; and (d) the percentage of perseverations out of the total number of errors generated. Each consonant correctly recalled was awarded 0.5 points and another 0.5 points were awarded if the consonant was recalled in the correct position, resulting in a total possible score of two points for each trial (total score = 42). For all errors, except switching and perseveration, zero points were awarded. In the case of switching, one point was awarded (0.5 points for each correct recall, but incorrect position). Perseverations were defined as the repetition of a consonant either presented or given as a response in the immediately preceding trial. In such cases, perseverations were scored according to the point system previously mentioned. A perseveration in an incorrect position was assigned

0.5 points, whereas a perseveration in the correct position was assigned one point. In order to evaluate the number of perseverations relative to overall number of errors made, a weighted score (W) was calculated, using the following equation:

$$W = \frac{C - \left(\frac{P}{(P+E)}P + \frac{E}{(P+E)}E\right)}{42}$$

C is the number of correct responses, P is the number of perseverative errors, and E is the total number of errors.

Dual-tasking. Dual-tasking was assessed using a modified version of the dual-task paradigm described by Della Sala et al. (2010). Firstly, an individual's ability levels for digit recall and tracking were calculated. For *digit span*, participants heard a list of digits, presented by a native English speaker, at a rate of one digit per second. They were then asked to repeat back these digits in the same order in which they heard them. Digits were initially presented at a sequence length of two. If two out of three sequences were correctly recalled, the sequence length was increased by one digit. This continued until a participant was no longer able to correctly recall two out of three trials at a given sequence length, and their 'digit span' was taken as the maximum sequence length at which participants could accurately recall two out of three trials.

For *tracking span*, participants were presented with a yellow dot (approximately four centimetres in diameter) that moved around the computer screen randomly. Participants were instructed to use the computer mouse to keep the cursor on the dot at all times. When contact was made, the dot changed colour from yellow to blue. Initially, the dot moved at approximately

3.5 centimetres per second. If the participant maintained contact with the dot for more than 60% of the time during a 15-second period, the speed of the dot was increased by 1 centimetre per second. If the participant maintained contact for 40-60% of the time during a 15-second period, then the speed remained constant. If the participant maintained contact for less than 40% of the time during a 15-second period, the speed decreased by 1 centimetre per second. Tracking span was taken as the maximum speed level at which the participant maintained contact with the dot for 40%-60% of the time during a 15-second period.

Participants were then asked to perform digit recall and tracking at their own individual span levels. During single task digit recall, participants performed digit recall at their span for 60 seconds. Performance was calculated as the percentage of correctly recalled digits in the correct serial position. During single task tracking, participants followed the moving dot around the screen at their individual tracking span for 60 seconds. Performance was calculated as the percentage of time that the participant maintained contact with the dot.

Finally, for *dual-tasking*, participants were asked to perform the two tasks simultaneously at their individual span levels for 60 seconds. Performance on each individual task was scored in the same way as the single conditions. In order to calculate proportional digit recall performance (p_d), the change in the percentage of correctly recalled digits between the single (d_{single}) and dual-task conditions (d_{dual}) was divided by the percentage of correctly recalled digits in the single condition (d_{single}):

$$p_d = \left\{ \frac{(d_{single} - d_{dual})}{d_{single}} \times 100 \right\}$$

Similarly, in order to calculate proportional tracking performance (p_t), the change in percentage of time the participant maintained contact between the single (t_{single}) and dual-task conditions (t_{dual}) was divided by the percentage of time the participant maintained contact in the single task condition. The following equation was used:

$$p_t = 100 - \left\{ \frac{(t_{single} - t_{dual})}{t_{single}} \times 100 \right\}$$

Finally, proportional digit recall performance (p_d) and proportional tracking performance (p_t) were summed, and divided by two, to give an overall proportional dual-tasking score (q):

$$q = \left\{ \frac{(p_d - p_t)}{2} \right\}$$

Proportional performance scores above 100% indicated an increase in performance during the dual-task condition, whereas proportional performance scores below 100% indicated a dual-task decrement.

Processing speed. Simple and choice reaction times were assessed using modified versions of the measures described by Baddeley, Chincotta and Adlam (2001). In the *simple reaction time (SRT)* test, participants were presented with a circle, approximately 5 centimetres in diameter, on a computer screen. They were asked to press the left arrow on the keyboard, using their right index finger, as quickly as possible, every time the circle appeared on the screen. Circles appeared at random intervals ranging from 1.6 to 4 seconds (M_{srt} = 2.8 seconds). Participants were given a practice trial of 30 seconds, followed by a reiteration of the instructions, and a test period of two minutes. Performance was calculated as the mean reaction time (RT).

For the *choice reaction time (CRT)* test, participants were presented with a circle or a square of the same dimensions. Using both index fingers, participants were instructed to press the left arrow each time a circle appeared, and the right arrow each time a square appeared, as quickly as possible. The shapes appeared at random intervals ranging from 1.6 to 4 seconds (M_{crt} = 2.8 seconds). Again, participants were given a practice trial of 30 seconds, followed by a reiteration of the instructions, and a test period of two minutes. Performance was indexed by mean RT, and the number of incorrect responses, converted to a percentage of the overall trials completed. Finally, the proportion of RT change between the *SRT* and *CRT* conditions (CRT/SRT) was then calculated (speed ratio).

Verbal intellectual functioning. Participants were administered the National Adult Reading Test (NART) (Nelson, 1982), as a measure of verbal intellectual functioning.

The total testing session duration was approximately 30 minutes and participants were allowed to take small breaks between tests, as needed.

Data analysis

To assess the normality of the distribution and the homogeneity of variance for each variable, Kolmogorov-Smirnov tests and Levene's tests were used respectively. Some of the data were not normally distributed despite log transformation. Therefore, performance of younger and older adults was compared using one-way analyses of variance (*ANOVA*) and analysis of covariance (*ANCOVA*), or Mann-Whitney tests, as appropriate. Additionally, between-group differences in education and NART IQ were also examined. For the executive measures, 2 (*Age*) x 2 (*Gender*) *ANOVAs* were conducted to examine the influence of both age and gender on performance. The relationships between performance on the tests of executive function and processing speed were also examined using Spearman correlational analyses, and adjusted using Bonferroni correction. The effects of age group, education, NART IQ and speed (*CRT/SRT*) on the executive tests were investigated using multiple regression analysis.

Results

Education and NART IQ

A two-way *ANOVA* with *Age* and *Gender* as factors revealed that the two age groups did not significantly differ in terms of their years of education, $F_{(1, 109)} = .258$, $p = ns$, nor was there a significant difference between genders, $F_{(1, 109)} = .003$, $p = ns$, nor a significant *Age* x *Gender* interaction, $F_{(3, 107)} = 1.707$, $p = ns$. However, a two-way *ANOVA* revealed that the older group had a significantly higher NART IQ than the younger group, $F_{(1, 109)} = 76.48$, $p < .001$, $\eta_p^2 = .417$, while there was no significant effect of *Gender*, $F_{(1, 109)} = .614$, $p = ns$, nor two-way interaction, $F_{(3, 107)} = .174$, $p = ns$.

Executive test performance

Table 1 displays the means and standard deviations of the younger and older groups on each of the tests of executive functioning.

- Insert Table 1 around here -

Inhibition – Colour Word Interference Test. A one-way *ANOVA* revealed the older group were significantly slower than the younger group both on the *Colour Naming*, $F_{1, 109} = 41.980$, $p < .001$, $\eta_p^2 = .267$ and *Word Reading* control conditions, $F_{(1, 109)} = 10.050$, $p < .01$, $\eta_p^2 = .085$. In the *Inhibition* condition, a two-way *ANOVA* revealed a significant main effect of *Age*, with the older group performing significantly slower than the younger group, $F_{(1, 109)} = 116.678$, $p < .001$, $\eta_p^2 = .479$. However, there was no significant main effect of *Gender*, $F_{(1, 109)} = .699$, $p = ns$, or a significant interaction, $F_{(3, 107)} = .036$, $p = ns$.

A further analysis was conducted to control for reading speed when examining the group differences on the *Inhibition* condition. When *Colour Naming* was entered as a covariate, the significant *Age* difference on the *Inhibition* condition remained, $F_{(1, 109)} = 53.496$, $p < .001$, $\eta_p^2 = .331$, although *Word Reading* speed did account for a significant amount of the variance, $F_{(1, 109)} = 56.117$, $p < .001$, $\eta_p^2 = .342$.

Set-shifting – Trail Making Test. A one-way *ANOVA* revealed that the older group were significantly slower than the younger group to complete *TMT-A*, $F_{(1, 109)} = 73.257$, $p < .001$, $\eta_p^2 = .413$, and *TMT-B*, $F_{(1, 109)} = 130.665$, $p < .001$, $\eta_p^2 = .545$. Analysing the *TMT proportion score (B/A)*, a two-way *Age* x *Gender ANOVA* also revealed a significant effect of *Age*, with the older group demonstrating a significantly larger proportional increase than the younger group, $F_{(1, 109)} = 13.54$, $p < .001$, $\eta_p^2 = .112$. However, no significant main effect was found for *Gender*, $F_{(1, 109)} = .25$, $p = ns$, nor a significant *Age* x *Gender* interaction, $F_{(3, 107)} = .117$, $p = ns$.

Updating – Brown-Peterson Task. . The older group made significantly fewer correct responses, $F_{(1, 109)} = 39.253$, $p < .001$, $\eta_p^2 = .265$, and a greater number of perseverations, $F_{(1, 109)} = 41.594$, $p < .001$, $\eta_p^2 = .277$, than the younger group on the *Brown-Peterson* task. A Mann-

Whitney test also revealed that the older group made a significantly greater proportion of perseverations relative to the total number of errors than the younger group, as calculated by the weighted score, $U = 584.500$, $z = -5.613$, $p < .001$, $\eta_p^2 = .284$. Comparing between genders in each age group separately, a Mann-Whitney test revealed no significant difference between males and females in neither the younger group, $U = 389.000$, $z = -.684$, $p = ns$, nor the older group, $U = 317.500$, $z = -.232$, $p = ns$.

Dual-tasking – Dual-Task Test. The younger group had a significantly longer mean digit span than the older group ($M_{younger} = 7.08$; $M_{older} = 6.62$), $F_{(1, 109)} = 4.921$, $p = .029$, $\eta_p^2 = .043$. Similarly, the younger group had a significantly faster mean tracking span than the older group ($M_{younger} = 11.49$; $M_{older} = 6.63$), $F_{(1, 109)} = 173.846$, $p < .001$, $\eta_p^2 = .615$). There was no significant age difference in single task *digit recall* performance ($M_{younger} = 88.43$ %; $M_{older} = 87.04$ %), $F_{(1, 109)} = 0.502$, $p = ns$; or single task *tracking* ($M_{younger} = 49.38$ %; $M_{older} = 51.69$ %), $F_{(1, 109)} = 0.839$, $p = ns$, when performed at span. There were also no significant group differences in dual-task *digit recall* performance ($M_{younger} = 87.55\%$; $M_{older} = 87.54\%$), $U = 1507.500$, $z = -0.158$, $p = ns$, or dual-task *tracking* performance ($M_{younger} = 47.24\%$; $M_{older} = 49.18\%$), $F_{(1, 109)} = .512$, $p = ns$, when performed at span. Finally, a two-way *ANOVA* revealed no significant difference between younger and older adults' proportional *dual-task* performance, $F_{(1, 109)} = .452$, $p = ns$, and no significant gender effect, $F_{(1, 109)} = .252$, $p = ns$, or *Age* x *Gender* interaction, $F_{(1, 109)} = .860$, $p = ns$. As the older group had a significantly higher NART IQ than the younger group, an *ANCOVA* was performed using NART proportional performance as a covariate. This revealed that even after partialling out the effect of NART, there remained no significant difference in dual-tasking between the two groups ($r = .114$, $p = ns$).

Speed of processing performance

Table 2 displays the mean performance of the two age groups on the measures of speed of processing.

- Insert Table 2 around here -

The older group had a significantly slower *SRT*, $F_{(1, 109)} = 42.315$, $p < .001$, $\eta_p^2 = .288$, and a significantly slower mean *CRT*, $U = 328.000$, $z = -7.127$, $p < .001$, $\eta_p^2 = -.457$, than the younger group. A two-way *Age* x *Gender ANOVA* also revealed that the older adults displayed a significantly greater increase in reaction time from the *SRT* to *CRT* conditions (speed ratio), $F_{(1, 109)} = 14.241$, $p < .001$, $\eta_p^2 = .117$, than younger adults. However, there no significant main effect of *Gender*, $F_{(1, 109)} = .102$, $p = ns$, or two-way interaction, $F_{(3, 107)} = .002$, $p = ns$, observed.

Relationship between age, executive tests and processing speed

Tables 3 and 4 demonstrate the relationship between performance on the executive and processing speed tests in the younger and older groups.

- Insert Tables 3 and 4 around here -

Performance on the processing speed measures was significantly intercorrelated, in both age groups. However, there was no significant relationship between any executive tests and processing speed in the younger group. In the older group, only one correlation was found, namely between performance on the CWIT *Inhibition* score and the *CRT*. However, when CWIT

Colour Naming performance was partialled out of the analysis, the relationship between the *Inhibition* score and *CRT* was no longer significant (younger group: $r = -.040$, $p = ns$; older group: $r = .239$, $p = ns$).

In the first regression model, age group ($p < .001$) and NART IQ score ($p < .05$) predicted performance on the *CWIT Inhibition* score, $F_{(4, 106)} = 33.46$, $p < .001$, $R^2 = 0.56$. Being in the younger age group and having a higher NART IQ predicted better *Inhibition* performance. Education and the speed ratio score were not significant predictors. In the *TMT proportion score* model, only age group was a significant predictor ($p < .001$) where older adults were poorer than younger adults were, $F_{(4, 106)} = 11.82$, $p < .001$, $R^2 = 0.31$. Education, NART IQ and speed did not significantly contribute to the model. For the *Brown-Peterson* weighted score, again only age group was a significant predictor ($p < .001$) where older adults were poorer than younger adults were, $F_{(4, 106)} = 10.27$, $p < .001$, $R^2 = 0.28$. None of the other predictors were significant. Finally, for proportional *dual-task* performance, the model had no significant predictors ($p = 0.29$, $R^2 = 0.05$).

Discussion

The aim of the current study was to examine the relationship between aging, speed of processing and executive test performance, including dual-tasking. The results revealed a significant effect of *Age* on tests assessing inhibition, task switching and updating. In particular, older adults performed significantly more slowly on the *Inhibition* condition of the *CWIT* and the switching component of the *Trail Making Test Part-B,* and made fewer responses and more perseverations on the *Brown-Peterson Task*. However, no significant effect of *Age* was found for dual-tasking. There was no significant effect of *Gender* on performance on any of the executive tests. When age, education, NART IQ and speed were entered into regression models, age was the significant predictor of performance for all executive tests except dual-tasking. Speed did not make any significant contribution on any fronto-executive test above age. These findings are in line with previous findings in the literature that report a significant effect of age on executive tests (Mittenberg et al., 1989; Daigneault et al., 1992; MacPherson et al., 2002; Fisk & Sharp, 2004; Lamar & Resnick, 2004).

Dual-task performance did not differ across the age groups, when calibrating task performance for individual ability. Although older adults had significantly lower digit and tracking spans than the younger adults, when the two individual tasks were performed simultaneously at their individual spans, there was no significant difference performance between the younger and older age groups. This supports previous dual-task studies where the tasks are performed concurrently at the individual's own ability levels (Baddeley et al., 1986; Della Sala et al., 2010; Logie et al., 2004; MacPherson et al., 2007). Dual-task studies that report age differences do not calibrate the tasks to the ability of each participant (Anderson et al., 1998; Craik et al., 1996; Craik & McDowd, 1987; Lindenberger et al., 2000). In the current study, the lack of *Age* effects when dual-tasking compared to other executive tests supports the notion that dual-tasking reflects a separable coordination executive function that does not decline with age (Della Sala et al., 2010; Logie et al., 2004; Baddeley et al., 2001; Baddeley et al., 1991).

This finding that age affects performance on some fronto-executive tests (i.e., inhibition, switching and updating measures) but not others (i.e., dual-tasking) speaks against the frontal lobe hypothesis of aging, which would predict that performance on all executive tests is vulnerable to healthy aging (Dempster, 1992; Moscovitch & Winocur, 1992; West, 1996; 2000). This is not novel as other cognitive aging studies have reported certain executive tests do not consistently show age-related differences (see MacPherson & Della Sala, 2015) such as the CET (Axelrod & Millis, 1994; Della Sala et al., 2003; Gillespie et al., 2002; MacPherson et al., 2014; Scarpina et al., 2015), letter fluency (Henry & Phillips, 2006; Lamar & Resnick, 2004; Parkin et al., 1995), as well as dual-tasking (Baddeley et al., 1991; Della Sala et al., 2010; Foley et al., 2011; MacPherson, Della Sala & Logie, 2007). Together these findings suggest that the frontal lobe hypothesis may be an oversimplification in terms of age effects on executive tests and the underlying causes for these differences should be explored further.

In terms of correlations between the different executive tests, only the *CWIT Inhibition* scores and *Brown-Peterson* scores correlated, and only in older adults. The lack of strong correlations among different executive tests supports previous findings in the literature and provides further evidence of fractionation of executive functions into separable functions (Duncan, Johnson, Swales, & Freer, 1997; Miyake et al., 2000; Teuber, 1972; Stuss, & Benson, 1986; Stuss, & Alexander, 2000; Shallice, 2002). It should be noted that fronto-executive tests may not correlate for other reasons such as low reliability, different strategy use, and task impurity (Burgess, 1997; Shallice & Burgess, 1996; Stuss & Alexander, 2000). As fronto-executive functions involve controlling lower-level processes, the non-executive processes involved in the tasks might influence performance as well as the executive ability the task taps. However, in support of the fractionation of executive functions, studies involving latent variable analysis that denote the common variance among multiple measures have also identified several executive factors (Miyake et al., 2000), including studies involving healthy older adults (Fisk & Sharp, 2004; Hedden & Yoon, 2006; Hull, Martin, Beier, Lane & Hamilton, 2008; Vaughan & Giovanello, 2010).

It was also examined whether any age effects on the fronto-executive tests administered could be explained by the differential impact of the task demands upon speed of processing. Although performance on the tests of simple and complex speed of processing did significantly differ across the age groups, there was no correlation between any measure of speed of processing and performance on the tests of executive functioning, in either age group. Moreover, the speed ratio score did not significantly predict performance on any executive test. It was perhaps somewhat surprising that performance on the executive tests did not correlate with processing speed. However, processing speed can be assessed in at least three different ways (see Deary, 2000): psychometric behavioural tests where participants must make simple decisions that would be completed correctly if sufficient time was provided (e.g., Digit Symbol-Coding subtest from the Wechsler Adult Intelligence Scales; Wechsler, 1997); cognitive-experimental psychology using simple and choice reaction times to assess processing speed, and psychophysical measures using inspection time. Arguably, the psychometric behavioural speed tests involve more complex decision-making, more akin to executive functions and these would be the tests that are related to executive performance. It is possible to have found a significant relationship between executive function and speed had the latter been assessed using measures such as Digit Symbol-Coding or Symbol Search. However, the current findings suggest that the effect of age upon the measures of executive functioning is independent of that on speed of processing, at least when assessed using cognitive-experimental psychology measures.

Neurobiological changes in the brain may also explain the lack of association between speed of processing and separable functions within the fronto-executive system in older age. For instance, older adults have been shown to display reductions in GABAergic function compared to younger adults (Maes et al., 2018). This GABA-related reduction in modulating cortical excitability has been linked to impairments in the perceptual, planning and motor systems that support speeded task performance. In contrast, within the fronto-executive system, dopamine transmission in the medial prefrontal cortex is thought to play a critical role in mediating set-shifting and attention, whereas serotonergic activity in the orbitofrontal cortex is thought to affect response inhibition (Logue & Gould, 2014); critically, the neurocircuitry involved in each is negatively altered as a function of age (Garrett et al., 2015; Meltzer et al., 1998). However, while studies examining associations between neuronal changes and age-related cognitive impairment now exist, there is still much that remains unknown.

Some authors consider performance on executive tests to simply be an additional indicator of Spearman's *g* (or general intelligence), especially its fluid abilities (g_f) (e.g., Salthouse, Atkinson & Berish, 2003). Significant relationships between intelligence and executive functions have been reported (Crawford, Bryan, Luszcz, Obonsawin & Stewart, 2010; Duncan, Burgess & Emslie, 1995; Duncan, Emslie, Williams, Johnson & Freer, 1996; Friedman et al., 2006; Salthouse & Davis, 2006). In particular, a strong association between g_f and working memory has been found (Friedman et al., 2006; Miyake et al., 2000; Redick, Unsworth, Kelly & Engle, 2012; Salthouse et al., 2003; Salthouse & Pink, 2008) and fairly modest relationships between g_f and executive tests such as verbal fluency, inhibition, and set-shifting have also been observed (Ardila, Pineda & Rosselli, 2000; Friedman et al., 2006; Miyake et al., 2000; Rabbitt & Lowe, 2000; Salthouse & Davis, 2006; Salthouse et al., 2003). Prior work has shown that g_f accounted for a large degree of variance on executive tests (Tower test, Self-Ordered Pointing Test) in a group of healthy older adults (Cox et al., 2014). One limitation of the current study was that it did not include a measure of g_f to consider its role in fronto-executive performance. However, the NART was included, which allowed for consideration of the role of crystallised intelligence (g_c). Analyses showed that NART IQ could not predict performance on any of the executive tests except for *Inhibition*, suggesting that not all executive functions relate to g_c. In line with this, Friedman and colleagues found that both g_f and g_c latent variables shared variance with their common executive factor, which includes a *CWIT* (i.e., the Stroop test; Friedman et al., 2006, 2008). They did not find that intelligence contributed to their other executive latent variables. Previous work involving patients with focal unilateral frontal lesions has also shown that age and NART IQ predict Stroop test performance (MacPherson et al., 2017).

In summary, this study suggests that aging has a differential impact upon discrete fronto-executive functions, with age-related decline in inhibition, switching and updating, but not dual-tasking. These findings do not appear to be explained by speed of processing, but rather suggest that dual-tasking is less vulnerable to the effects of age. These results have important clinical implications, as a dual-task deficit in older adults might be considered a specific marker of pathological aging (Baddeley et al., 1991; Della Sala et al., 2010; Foley et al., 2011, 2013; Kaschel et al., 2009; Logie et al., 2004; MacPherson et al., 2012).

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Table 1. Means and standard deviations for younger and older adults performing the executive function measures

Measure		***Younger Adults***				***Older Adults***				***Age effect***
		Female		***Male***		***Female***		***Male***		
		M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***p***
Inhibition	CWIT – Colour Naming (s)	24.42	2.90	24.79	3.45	29.00	5.46	31.82	6.33	<.001
	CWIT – Word Reading (s)	18.71	2.47	18.64	3.68	20.1	3.04	21.32	3.71	<.01
	CWIT – Inhibition (s)	40.61	7.18	41.86	8.55	60.77	11.17	64.09	16.76	<.001
Set-shifting	TMT – Part A (s)	23.92	5.94	21.66	5.06	34.33	8.92	36.22	9.83	<.001
	TMT – Part B (s)	43.64	8.50	42.46	10.49	78.70	24.06	83.61	31.21	<.001
	TMT – Part B/PartA (s)	1.9	0.49	1.99	0.36	2.32	0.60	2.34	0.74	<.001
Updating	BP – Correct	36.44	3.59	37.16	3.12	31.27	5.16	31.05	6.84	<.001
	BP – Errors	5.57	3.59	4.84	3.12	10.67	5.07	10.96	6.84	<.001
	BP – Perseverations	1.52	1.30	1.52	1.57	4.27	2.77	3.82	2.51	<.001
	BP – Weighted Score	75.06	16.03	78.44	13.73	52.82	22.40	51.57	30.39	<.001
Dual tasking	Digit Recall	100.2	15.01	99.17	16.28	100.64	10.63	105.23	15.09	*ns*
	Tracking	99.26	23.25	98.3	24.26	91.30	21.43	93.42	20.46	*ns*
	Overall proportional performance (%)	99.74	12.62	98.74	12.9	95.97	11.19	99.34	12.50	*ns*

CWIT = Colour-Word Interference Test; TMT = Trail Making Test; BP = Brown Peterson task; *ns* = non-significant

Table 2. Performance of younger and older adults on the measures of processing speed

Measure		***Younger Adults***				***Older Adults***				***Age effect***
		Female		***Male***		***Female***		***Male***		
		M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***p***
SRT	Mean Reaction Time (ms)	239.00	22.65	238.21	28.82	273.62	31.43	272.13	28.93	<.001
CRT	Mean Reaction Time (ms)	397.12	69.22	391.82	45.07	20.10	3.04	21.32	3.71	<.001
	Percentage incorrect (%)	2.74	2.19	2.47	2.36	2.26	2.58	2.41	2.91	*ns*
CRT/SRT	Proportional performance (%)	1.67	0.28	1.65	0.14	1.84	0.24	1.83	0.28	<.001

SRT = Simple Reaction Time; CRT = Choice Reaction Time; *ns* = non-significant

Table 3. Spearman correlations between performance on measures of executive functioning and processing speed in the younger group

	CWIT Inhibition (s)	***TMT B/A (s)***	***BP Weighted score***	***Dual task Overall (%)***	***SRT (ms)***	***CRT (ms)***
TMT – B/A (s)	-.02					
BP – Weighted score	-.13	.08				
Dual task – Overall (%)	-.03	-.01	.08			
SRT (ms)	.06	-.08	-.16	.10		
CRT (ms)	.25	.04	-.16	.07	.52*	
CRT/SRT (ms)	.11	.07	-.04	-.05	-.28	.60*

* $p < .05$; ** $p < 0.01$; *** $p < 0.001$

CWIT = Colour-Word Interference Test; TMT = Trail Making Test; BP = Brown Peterson task; SRT = Simple Reaction Time; CRT = Choice Reaction Time

Table 4. Spearman correlations between performance on measures of executive functioning and processing speed in the older group

	CWIT Inhibition (s)	***TMT B/A (s)***	***BP Weighted score***	***Dual Task Overall (%)***	***SRT (ms)***	***CRT (ms)***
TMT – B/A (s)	.09					
BP – Weighted score	-.45*	-.37*				
Dual task – Overall (%)	.09	-.03	.31			
SRT (ms)	.08	.08	-.24	-.32		
CRT (ms)	-.43*	-.05	-.14	-.04	.23	
CRT/SRT(ms)	.25	-.10	.08	.15	-.61*	.57*

* $p < .05$; ** $p < 0.01$; *** $p < 0.001$

CWIT = Colour-Word Interference Test; TMT = Trail Making Test; BP = Brown Peterson task; SRT = Simple Reaction Time; CRT = Choice Reaction Time